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FINAL REPORT
PROGRAM 461 RELIABILITY
MATERIALS RESEARCH AND APPLICATION
EVALUATION OF BEARING MATERIALS AND LUBRICANTS FOR SPACE ENVIRONMENT

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FOREWORD

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The activity described in this document was performed primarily by the Process Development Group of the LMSC Materials Sciences Laboratory.

CONTENTS

CONTENTS (Continued)

TABLES

ILLUSTRATIONS

Appendix A

TABLES

Appendix B

SECTION 1
INTRODUCTION

1.1 SCOPE

This report presents evaluations of certain lubricants and self-lubricating materials that were considered for use with ball bearings in space environments. The two criteria used to evaluate bearing lubricants were coast time and lifetime. Coast time, as herein considered, is the length of time taken by motors running at 8,000 rpm to come to a full stop after being shut off and is used as an indication of running torque. Lifetime is the total length of operating time a motor will run on one set of bearings before stalling. The target established for a satisfactory lifetime was two years.

Six types of lubricant means were tested: oils, grease, molybdenum-disulfide films, special retainer materials, soft metal films, and bearings containing plastic balls.

A space environment was approximated with vacuum chambers with vacuums reached ranging from 10^{-6} to 10^{-9} torr.

This report includes both the test results obtained up to 15 August 1962 as previously reported in LMSC-A082405, and the running times obtained on or before 6 March 1963 for the tests still in operation at that date.

SECTION 2
SUMMARY AND CONCLUSIONS

The best operating lifetimes in a vacuum were achieved with oil and grease lubricants. Of the 37 tests conducted with 28 oils, double-shielded bearings with vacuum impregnated paper base phenolic retainers lubricated with 4 oils (one low-volatility petroleum base oil and 3 halogenated silicones) gave lifetimes of over 1 year. Of 13 greases evaluated in 16 tests, 4 greases, composed of silicone oils in shielded bearings showed lifetimes of over 1 year. On the basis of coast times, torque was about the same for oil-lubricated bearings with phenolic retainers as for the grease-lubricated bearings with metal-ribbon retainers. Of the total oil tests in a vacuum, 1 oil (Apiezon K) has achieved 18,297 hours of test time and is still running. Of the total grease tests in a vacuum, 1 grease (Aeroshell-15) has achieved 13,364 hours and is still running.

Of the 29 tests conducted, on different dry-film lubricants[1], 15 showed poor reproducibility and all had limited lifetimes under a 100 percent duty cycle. The maximum lifetime achieved was 2,213 hours. However, similar tests on the same material gave test times of 876, 245, 342, and 132 hours.

Eight self-lubricating retainer materials were evaluated in nineteen tests. Two polytetrafluoroethylene compositions gave the best results: 5,000 and 3,000 hours.

Tests with silver plated balls conducted by a subcontractor showed limited lifetimes. The maximum lifetimes achieved yielded times between 2,000 and 3,000 hours. The lifetimes were strongly dependent on processing techniques, and some doubt exists as to process control.

Initial work done with plastic ball bearings, while holding promise as a space bearing lubricating method, will require improved fabrication techniques before consistent test results can be expected.

[1] A different method of application was considered to be a different lubricant.

Small running torque changes proved to be no indication of impending failure of the bearings.

In conclusion, this study has shown that with a proper choice of lubricant system (measured against torque, temperature, duty cycle and other design requirements) operational lifetime expectancies of two years in Program 461 space environments of these devices are practical.

SECTION 3
EQUIPMENT AND PROCEDURES

3.1 LUBRICANTS

The following types of lubricant systems were evaluated:

- Oil
- Grease
- Molybdenum-disulfide based films
- Special retainer materials

In addition, silverplated steel bearings and those containing plastic balls were tested under subcontracts. These types are discussed in paragraphs 4.5 and 4.6.

3.2 BEARINGS

Table 3-1 lists the types of ball bearings that were used. The lubricant tested determined the choice of a particular bearing.

Table 3-1
TYPES OF TEST BEARINGS

Type	Lubricant	Bearing Material	Bearing Description	Supplier
1	Oil and grease	440C	Deep groove, ribbon retainers, double shielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	Barden Corp.
2	Oil and grease	52100	Deep groove, ribbon retainers, double shielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	Barden Corp.

Table 3-1 (Continued)

Type	Lubricant	Bearing Material	Bearing Description	Supplier
3	Oil	440C	Deep groove, paper base phenolic retainers, double shielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	Barden Corp.
4	Oil	52100	Deep groove, paper base phenolic retainers, double shielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	Barden Corp.
5	MoS_2	440C	Deep groove, ribbon retainers, unshielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	Microtech
6	Rulon "C" Duroid 5813 Nylasint (Special retainer)	440C	Angular contact, double shielded R-3 size (3/16 inch bore, 1/2 inch outside diameter) ABEC Class 7	New Hampshire Ball Bearing Co.
7	Sinitex Sinite (Special retainer)	440C	Angular contact, unshielded	Industrial Techtronics, Inc.
8	Soft Metal Film (silver)	440C(1) 52100 M50	R3H (3/16 inch bore, 1/2 inch outside diameter) No retainer	
9	None	52100(2)	204 size with plastic balls.	Marlin Rockwell

(1) See Soft Metal Film Lubricant Study, Final Technical Report LMSD-TR-61 prepared by Machlett Laboratories, Inc., Springdale, Connecticut.

(2) See Evaluation of Stainless Steel Bearings Incorporating Plastic Balls, Final Report M-R-C Research Proposal No. 1468 prepared by Marlin-Rockwell Corporation, Jamestown, New York.

3.3 TEST MOTORS

Figure A-1 (see Appendix A) shows a disassembled motor of the first type used. The motor shaft was machined to fit the 3/16-bore diameter of each bearing. The motor bell housings were machined with openings to aid in exposing the bearings to the vacuum. The exposed stator windings can be seen in the photograph. In the initial tests the absence of convective cooling caused these motors to overheat when operated above 100 volts in a vacuum. This overheating caused excessive outgassing and breakdown of the varnish insulation which, in turn, short circuited the stator windings. The motor voltages were thereafter kept in the range of 70 to 90 volts during operation in a vacuum to minimize possible contamination of outgassed material on the lubricant under test.

Figure A-2 shows the motor currently used in the LMSC laboratory portion of this test program. It has a "canned" stator to prevent outgassing and employs polytetrafluoroethylene (PTFE) insulation to allow higher-temperature use. It has been successfully operated in a vacuum at 300 degrees Fahrenheit for over 4,000 hours.

3.4 BEARING LOAD

The radial load on the bearings was that of the equally distributed rotor weight. The original motor had a radial loading of 155 to 165 gm (5.6 ounces), while the newer motors range from 270 to 280 grams (9.7 ounces). Bearings were slip fit to shafts of each motor that had been machined to tolerances recommended by bearing manufacturers. Outside diameters of bearings were slip fit to their supporting bell housings. This procedure allowed some confidence in the loading of each bearing under increased test temperatures. No axial load was used except in some tests with the special retainers. For ease of assembly, the bearings for testing these special retainers were of an angular contact type. Axial loads of 1/4, 1/2, and 1 pound were applied to both bearings through the use of a loading spring, bearing against the outer races of each bearing.

3.5 RUN-IN PROCEDURE

The bearings were given an initial run-in at 8000 rpm for a 24-hour period before oil or grease lubricants were applied to bearings with ribbon retainers.

Motors were then disassembled, bearings shields removed, and the bearings ultrasonically cleaned. Upon removal from the cleaning bath each bearing was examined under a 30-power glass for pits, scars or other mechanical features of the bearing's condition that might affect test results.

Bearings with phenolic retainers were not run in, but were used as delivered after vacuum impregnation of the test oil.

Special retainer bearings were also not run in but were installed and tested as received.

3.6 LUBRICATION PRACTICE

Bearings with metal retainers scheduled to receive oil lubricants were weighed, dipped, drained of excess, re-weighed, and reassembled to run-in motors.

Bearings with metal retainers scheduled to receive greases were weighed, disassembled and each ball pocket individually greased. They were then reassembled, re-weighed, and installed in the run-in motor.

Bearings with phenolic retainers were weighed and vacuum impregnated as received at room temperature by placing them in a vial containing test lubricant in a vacuum chamber. The chamber was evacuated and held in a vacuum state until bubbling ceased. This was normally a 2 to 3 hour process. After impregnation each bearing was re-weighed and installed in its vacuum test motor.

To test the molybdenum-disulfide films, unassembled, unshielded bearings were supplied to the lubricant manufacturer for application of the film. The bearings were then reassembled by the bearing manufacturer. The bearing to which the lubricant was applied was operated back and forth slowly by hand and blown out with clean, dry gas. This procedure was repeated several times. The bearings were then assembled to their motors and operated at four rpm for approximately ten minutes, stopped, blown out and run at four rpm in the opposite direction for ten minutes. This operation was repeated until the bearings had run from 30 to 60 minutes. The same procedure; run, blow-out, and reverse was followed at 8,000 rpm for 20 to 30 minutes.

In all testing both bearings on any one motor received the same lubricant, which was applied at the start of a test and was not replenished.

3.7 VACUUM SYSTEMS

Motors were then placed in the vacuum chamber and the system evacuated. Oil diffusion pumps with liquid nitrogen traps were used in most of the testing of oils and greases, and ion pumps were used in all testing of dry-film lubricants and special retainer materials.

Figure A-3 shows a typical chamber evacuated by a 6-inch oil diffusion pump used for tests with oils and greases. Eight motors were run simultaneously in the 18-inch bell jar of this system. The system is provided with an optically tight liquid-nitrogen trap designed so that oil from the diffusion pump must migrate over a surface at liquid-nitrogen temperature to reach the chamber. This procedure assured absence of lubricating properties to the test bearings by the vacuum pump oil. This unit is normally capable of sustaining a pressure of 2 to 3×10^{-8} torr when all eight motors are in operation and has operated at 9×10^{-9} torr for short periods.

Three other systems evacuated by diffusion pumps maintained pressures during testing from 2×10^{-7} torr to 1×10^{-9} torr. The lowest pressure maintained for periods of several hours or more was 6×10^{-10} torr.

Chamber pressure was measured with a modified Bayerd-Alpert ionization gauge that was connected to the baseplate by 5/8-inch ID tubulation.

Figure A-4 shows a typical chamber evacuated by an ion pump. Several sizes of chambers and pumps were used. Stainless steel chambers ranged from 6-inch ID by 10-inches long to 14-inch ID by 20-inches long; pumps ranged in rates from 90 to 360 liters/second. Pressures reached ranged from 4×10^{-6} to 2×10^{-8} torr.

3.8 TEST METHODS

3.8.1 Time Recording System

Each motor placed in the vacuum chamber was connected with a controllable d-c power source. This connection was in series with a running time meter and a slow-blow fuse, selected so that upon motor reaching a stall condition the fuse would open and stop power both to the motor and its timer.

3.8.2 Speed and Direction of Rotation

The controlled bearing speed, measured with a strobe light, was set at 8,000 rpm. Rotation in most tests was unidirectional. However, some start-stop-reverse tests were run on bearings with the molybdenum-disulfide films and some with special retainers. The start-stop-reverse operation was sequenced as follows:

- Fifty-two minutes in one direction at 8,000 rpm
- Eight minutes power off (this includes coast and some stop time)
- Fifty-two minutes at 8,000 rpm in the opposite direction
- Eight minutes power off and repeat.

The unidirectional tests were continuous wherever practical; however, some failures of support equipment were experienced.

3.8.3 Temperature

In most tests the temperature at the bearings was 160 to 200 degrees Fahrenheit, as measured by iron-constantan thermocouples attached to the bearing housings. This temperature was due in part to power losses in the motor and friction created in the bearings. To further evaluate those lubricants that appeared promising from early tests, tests were conducted using these same lubricants at 225 and 300 degrees Fahrenheit temperatures. In these tests radiant heating was used to control temperatures at the thermocouples.

3.9 EVALUATION CRITERIA FOR LUBRICANTS

The two criteria used to evaluate the bearing lubricant system were coast time and lifetime. Coast time as herein considered is the time required by the motors to slow down from 8000 rpm to a full stop when the power to the motor is cut off. This criteria was used as an indication of running torque of the pair of bearings and was checked approximately once a week. Coast time of all tests are presented in Table B-1. Coast time proved to be no indication of incipient failure, as some bearings failed within two hours of weekly check time.

Lifetime is the length of time a motor operates on a set of bearings before increase in bearing torque is sufficient either to stall the motor or to prevent its being restarted following measurement of the coast time. A stalled rotor increased the motor current sufficiently to blow the circuit fuse, thereby cutting off power to the motor and its timer.

SECTION 4
RESULTS

4.1 OILS

Table B-1 gives pertinent data of tests made with oil lubricants. Tests were started at the beginning of the program on four oils with motors running in air and with motors running in vacuum. Tests 5, 16, 23, and 32 were run in air and are still running. Of the four tests run in vacuum using the same lubricants, only one, number 15, is still running.

Double shielded bearings were used in all tests. Best results were obtained with phenolic retainers. For example, Test 1 with a ribbon retainer and with Versilube F 50 failed after 4,574 hours. The same oil with a phenolic retainer failed at 13,053 hours. The retainer used was a pinned two-piece paper base phenolic with seven ball pockets.

The causes of failure of the oil-lubricated bearings were:

- Partial loss of lubricant
- Decomposition of the residue

Figure A-5 shows bearings with a polyphenyl ether which failed after 2,400 hours (Test 31). Despite the vacuum operation, the decomposition products were similar to those encountered in an air atmosphere.

4.2 GREASES

Table B-2 presents the data of the tests made with greases. The longest lifetime to date was achieved in a double shielded bearing lubricated with Aeroshell 15, a methyl-phenyl silicone oil with dye thickener. This test (Test 5) is still running after 13,000 hours.

Two other silicone oil-based greases EG-429 and EG-509 from Marlin Rockwell are also still running after 9,000 hours (Tests 9 and 10) under similar conditions.

Good results were obtained with Versilube G-300 grease which is Versilube F-50 with a lithium soap thickener. Test No. 1 (Table B-2) ran 9,600 hours before failure. Test No. 3 at 225 degrees Fahrenheit is still running after 8,200 hours. Test No. 4 at 300 degrees Fahrenheit failed at 4,359 hours.

Primary cause of failure in all grease tests was loss of oil and decomposition of the thickener. A typical illustration is shown in Figure A-6, which is a post-test photograph of two test bearings lubricated with Versilube G-300 (Test No. 1).

4.3 DRY-FILM LUBRICANTS

All dry-film lubricants tested contained a molybdenum-disulfide base. Results of the tests are given in Table B-3 and indicated limited lifetimes and poor reproducibility. Results varied significantly even though all the parameters were kept constant.

The best material evaluated, Hi-T-Lube, showed 1,500 hours of unidirectional operation (Test 25) and over 1,000 hours in reversal testing (Test 26).

Tests 1 through 6 demonstrated the poor reproducibility of molybdenum disulfide-based lubricant films. The lifetimes varied from 132 to 2,000 hours.

The primary cause of failure in the film lubricated bearing was the breaking of the ribbon retainer. A typical failure is shown in Figure 7, (Test 25) which failed after 1,500 hours. Differences in results were noted between applications of dry-film lubricants to the races, retainers, or balls. Insufficient testing has not permitted proper correlation of application preferences. This study has found ribbon retainers to be unsatisfactory when used with dry-film lubricants.

4.4 SPECIAL RETAINERS

The data obtained from the performance of tests using special retainers is given in Table B-4. The best material evaluated was Rulon C, a Teflon-base composition which had a lifetime of 3,100 hours (Test 1). Another test of this material is still running after 3,883 hours of reversal testing (Test 3).

Duroid 5813, a Teflon composition containing molybdenum disulfide gave good results with a 0.25-pound-thrust load (Test 7). However, increasing the thrust load or using reversal testing reduced the lifetime to 90 hours (Test 8).

Typical causes of failure were wear of the ball pockets, with subsequent jamming of the bearing by the wear debris, or break-up of the retainer. Figure A-8 shows the retainers from Test 1 with Rulon C after 3,100 hours. The enlargement of the ball pocket and a crack between two pockets can be seen. Figure A-9 shows the broken retainers of sintered nylon which failed after 27 hours (Test 10).

4.5 SILVER FILM

Tests with silver-plated balls were run under Subcontracts 28-1274 by the Machlett Laboratories, of Stamford, Connecticut. Results of these tests are contained in the Final Technical Progress Report, Soft Metal Film Lubricant Study, LMSD-TR-61.

The longest lifetimes achieved were between 2,000 and 3,000 hours in three of many tests. Studies show lifetimes are directly related to the manner in which the balls were processed. Processing techniques depend on the substrate of the balls. At the present time, these techniques are not an established method of production on substrates investigated.

4.6 PLASTIC BALLS

Bearings, size -204, with plastic balls were manufactured and tested by the research laboratories of Marlin-Rockwell Corporation, Jamestown, New York. The results of this evaluation are given in Evaluation of Stainless Steel Bearings Incorporating Plastic Balls, Final Report M-R-C Research Proposal No. 1468. These bearings showed higher torques than did equivalent-sized steel bearings. Difficulty was encountered in assembling the bearings and in holding and checking tolerances. It is recommended that in any future tests of this system, plastic retainers (nylon or phenolic) be used with these bearings. As an alternate approach, some consideration should be given to the use of plastic races with the steel balls and plastic retainers.

SECTION 5
DISCUSSION

5.1 VALIDITY OF TESTS

The validity of testing the oil and grease lubricated bearings in chambers evacuated by oil diffusion pumps and of testing more than one lubricant in the same chamber may be questioned. However, because of the following considerations we believe that the test results are valid under these conditions. Backstreaming is reduced by baffling and by use of liquid nitrogen traps. Any backstreaming or cross contamination would be expected to deposit on the cold walls of the chamber rather than to pass around a shield and onto the bearing surfaces (which are hotter than the chamber). A test of an unshielded, unlubricated bearing, run in a vacuum chamber evauated by a diffusion pump, failed at 25 hours. A test with the vacuum pump oil in a double-shielded bearing ran only 2600 hours in vacuum in comparison with the 18,000 hours of operation in vacuum achieved with a petroleum base oil. If vacuum pump oil had been appreciably contributing to bearing life, greater uniformity and length of lifetimes would have resulted in all testing using this system. As noted, the lifetimes varied from 164 hours with a phosphate ester to 18,000 hours of operation with the above-mentioned petroleum oil.

5.2 CHEMICAL COMPOSITION AND VAPOR PRESSURE

Attempts were made to correlate performance on oils with more easily measured lubricating properties. Although this was largely unsuccessful, two properties do appear important for using oils under vacuum conditions. These are vapor pressure and inherent lubricating qualities. The inherent lubricating qualities will be influenced by the tendency of the oil to some type of reaction or absorption on the surface being lubricated. Neither of these properties alone is sufficient to correlate data. However, provided other factors are held constant, lifetime is improved by using oils with either lower vapor pressure or better lubricating qualities. As an example, Table 5-1 compares data on lifetime and vapor pressure in the same type bearing for four highly refined petroleum oils of the same class and from the same manufacturer. It can be assumed that the tendencies of these oils to react or be absorbed on the bearing surfaces is small and similar for all four oils. With this factor held relatively constant, the lifetime is seen to vary inversely with the vapor pressure, being longest for the oil having lowest vapor pressure. It is also worth noting that the viscosities of these oils increase as their vapor pressure decreases, so that the oil that provided the longest lifetime did so even though it is an extremely viscous material and would not normally be considered desirable as a lubricant for ball bearings operating at high speeds.

Table 5-1

VAPOR PRESSURE AND OPERATING TIME IN VACUUM OF A CLASS OF PETROLEUM OILS

Test Number (Table B-1)	Oil	Vapor Pressure (torr)	Temperature (degrees F)	Operating Lifetime (hours)
19	B	1×10^{-8}	77	790
20	C	1×10^{-8}	77	1,713
18	J	10^{-8} approx. 10^{-3}	77 482	7,093[a]
15	K	10^{-8} to 10^{-9} 10^{-3}	77 572	18,297[a]

[a] Still running

In the tests in vacuum with silicon-E oils, summarized in Table 5-2, the dimethyl polysiloxane gave the shortest lifetime, a methylphenyl polysiloxane was intermediate, and halogenated silicones – both a chlorophenyl methyl polysiloxane and a fluorosilicone gave the longest lifetime. This ranking is consistent with the known lubricating qualities of these silicone oils in air. Halogenation, which is known to promote better lubrication in the silicone oils, appears to be effective in vacuum as well as air.

Table 5-2

PERFORMANCE OF SELECTED SILICON OILS IN VACUUM

Test Number (Table B-1)	Oil	Operating Lifetime (hours)
7	Dimethyl polysiloxane	347
9	Methyl phenyl polysiloxane	6,066
2	Chlorophenyl methyl polysiloxane	13,652
13	Fluorosilicone Oil	9,874

5.3 FUTURE WORK

When the vacuum tests described in this report were first started, it was hoped that eventually the results of these tests could be correlated with more basic properties of lubricants, measurable in short-time tests. That goal was not attained, however, despite some of the tentative qualitative conclusions that have been set forth. Future work should seek to

- Obtain data on larger sample sizes in order to provide a sound basis for attempting correlation of lubricating properties.
- Examine performance data of oils in vacuum with other basic lubricating properties.
- Start development of bearings incorporating into their construction labyrinth seals to slow evaporation of oils and greases.
- Investigate the use of sintered porous steels as lubricant storage areas in rolling element bearings.

APPENDIX A
ILLUSTRATIONS

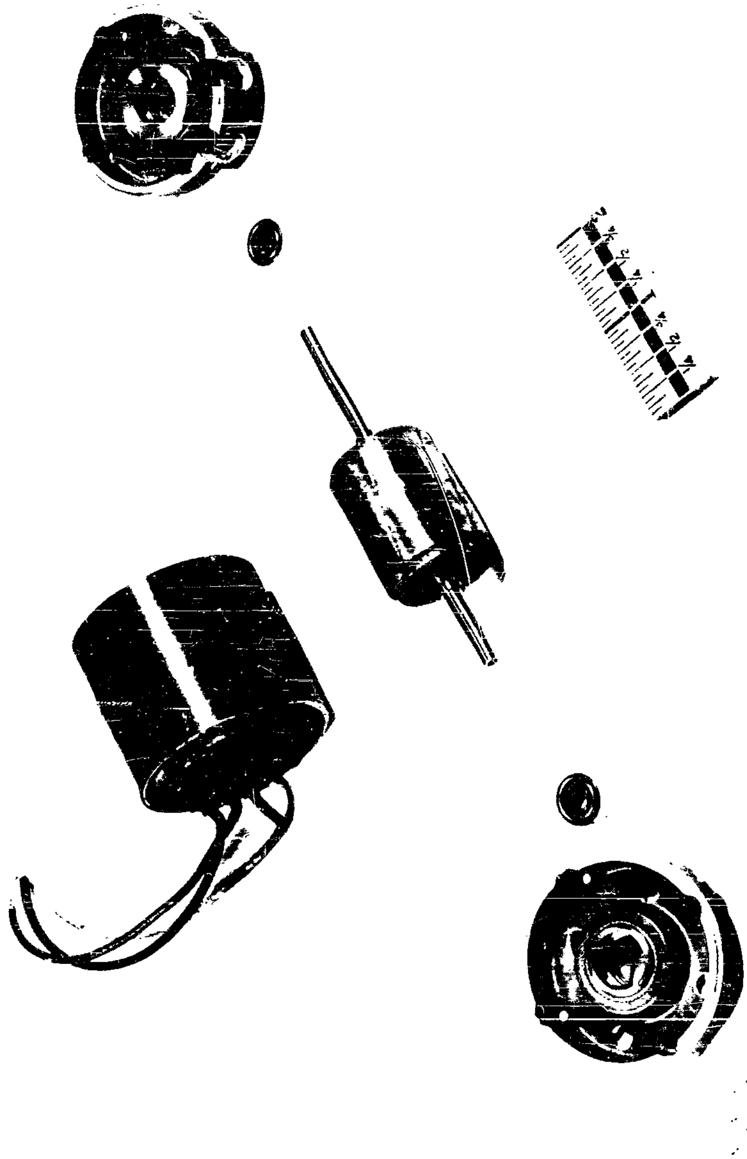

Figure A-1 Test Motor of Original Type

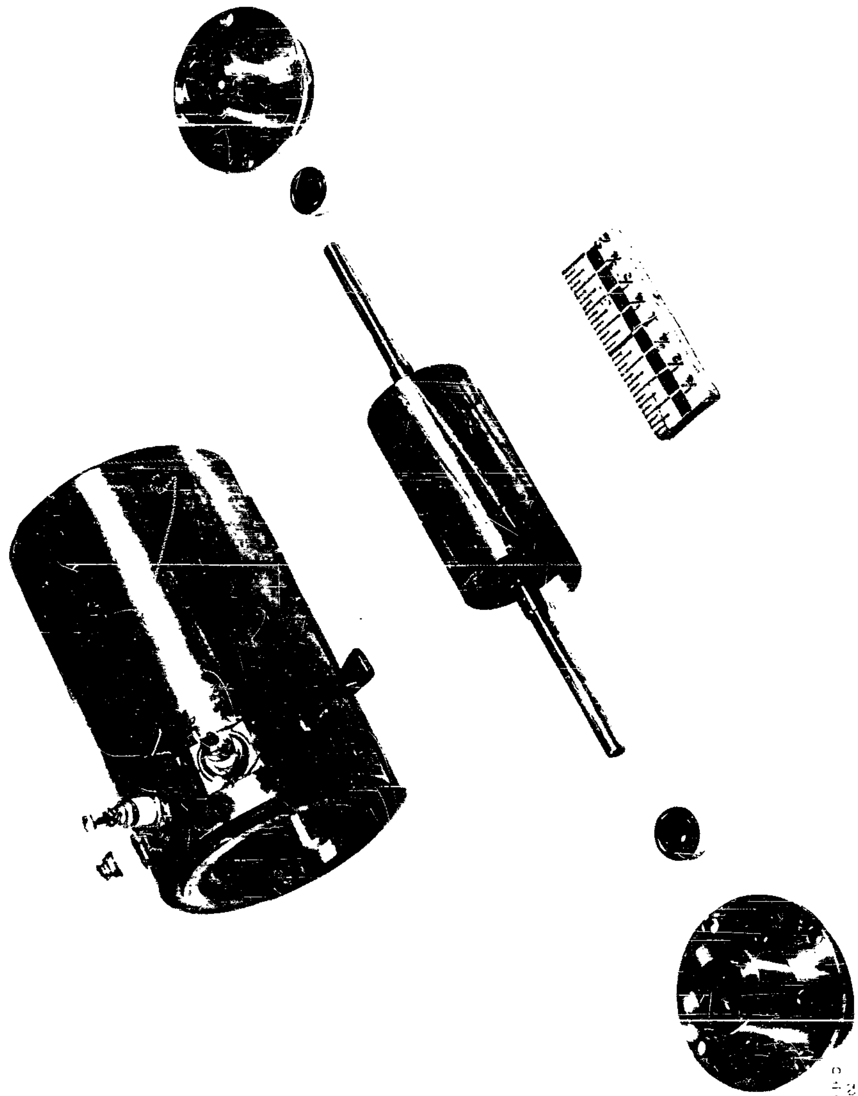

Figure A-2 Test Motor of Latest Design

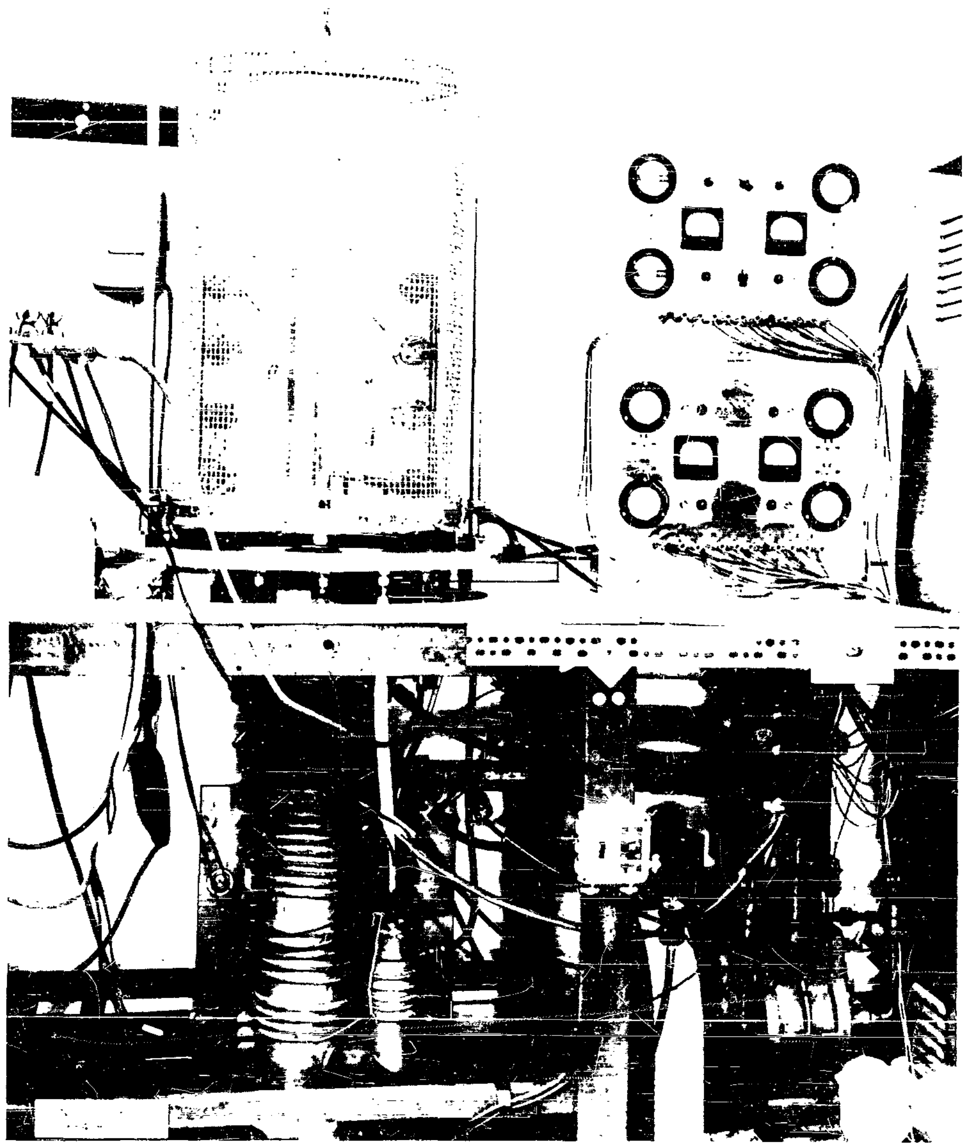

Figure A-3 Test Set-up with Oil Diffusion Pump

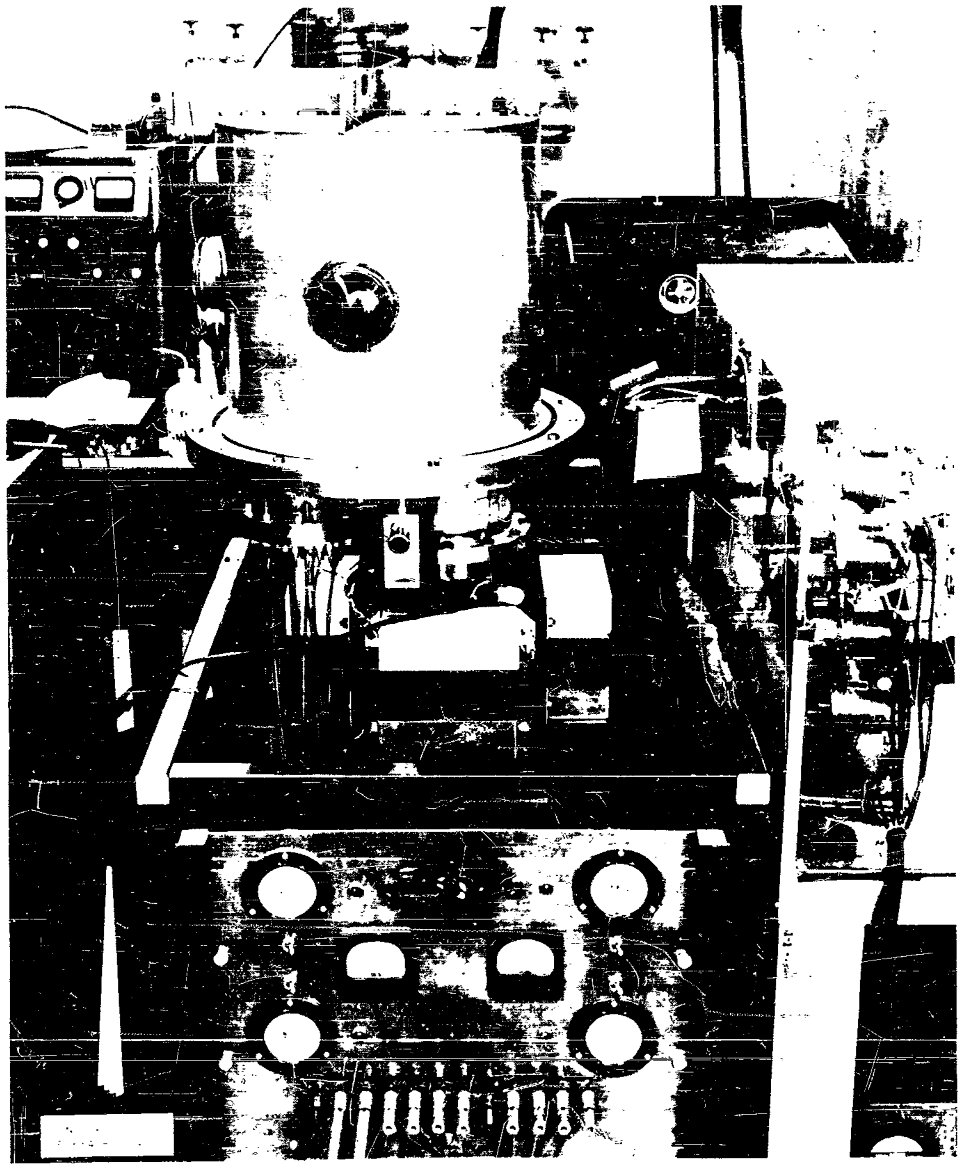

Figure A-4 Test Set-up with Ion Pump

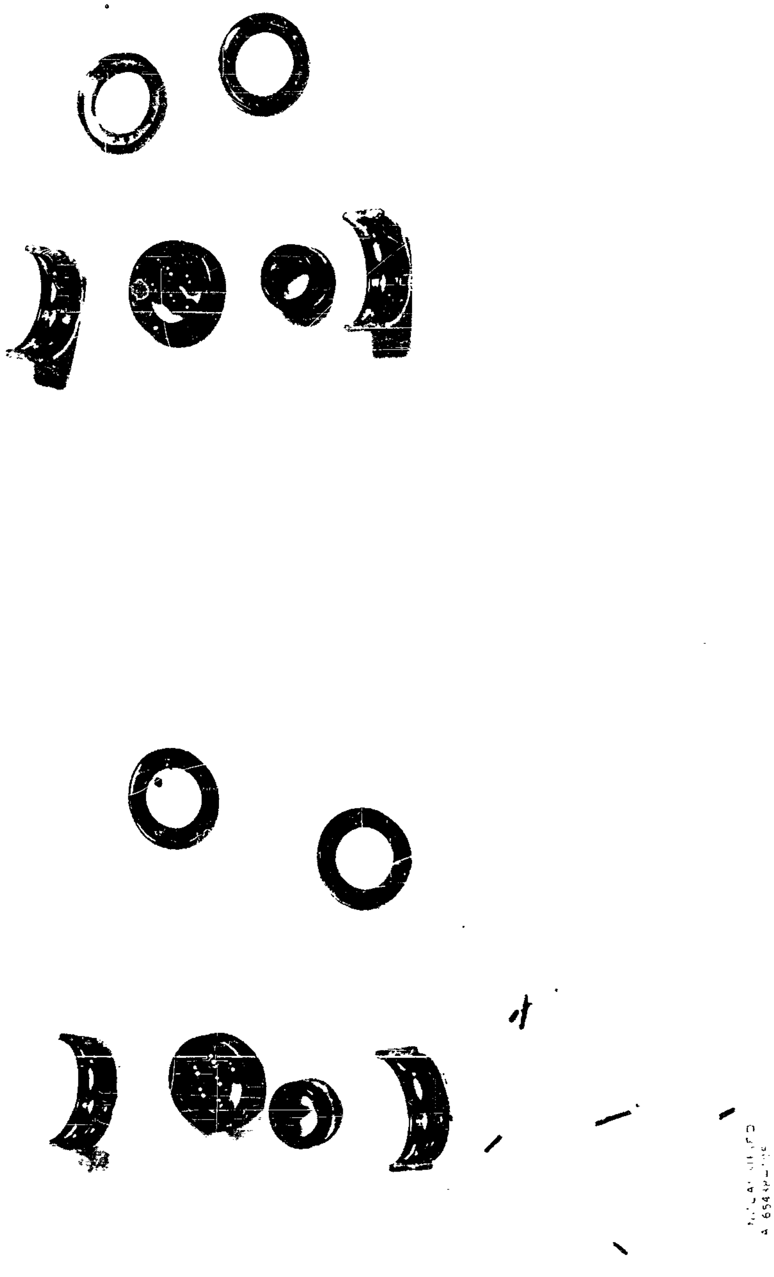

Figure A-5 Failed Oil Lubricated Bearings

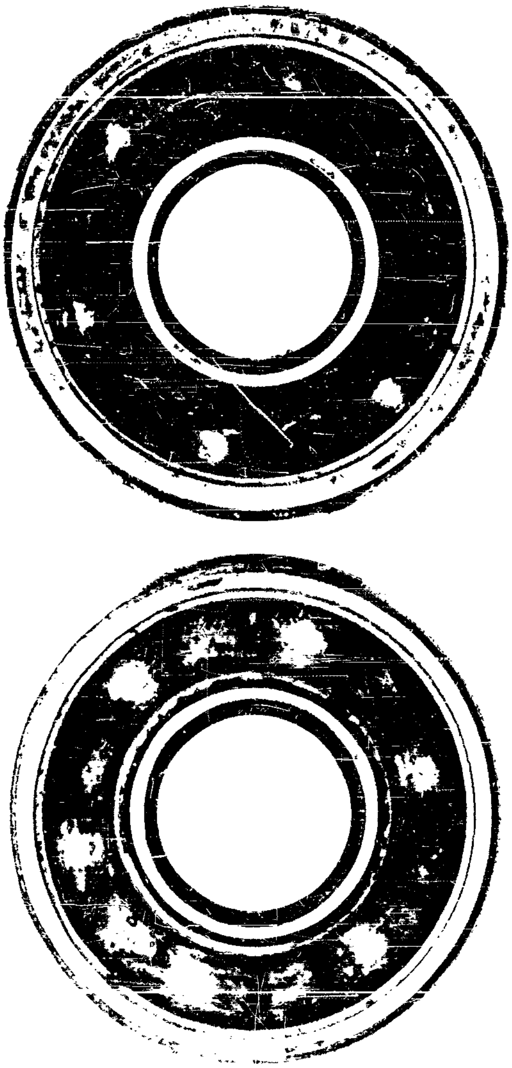

Figure A-6 Failed Grease Lubricated Bearings

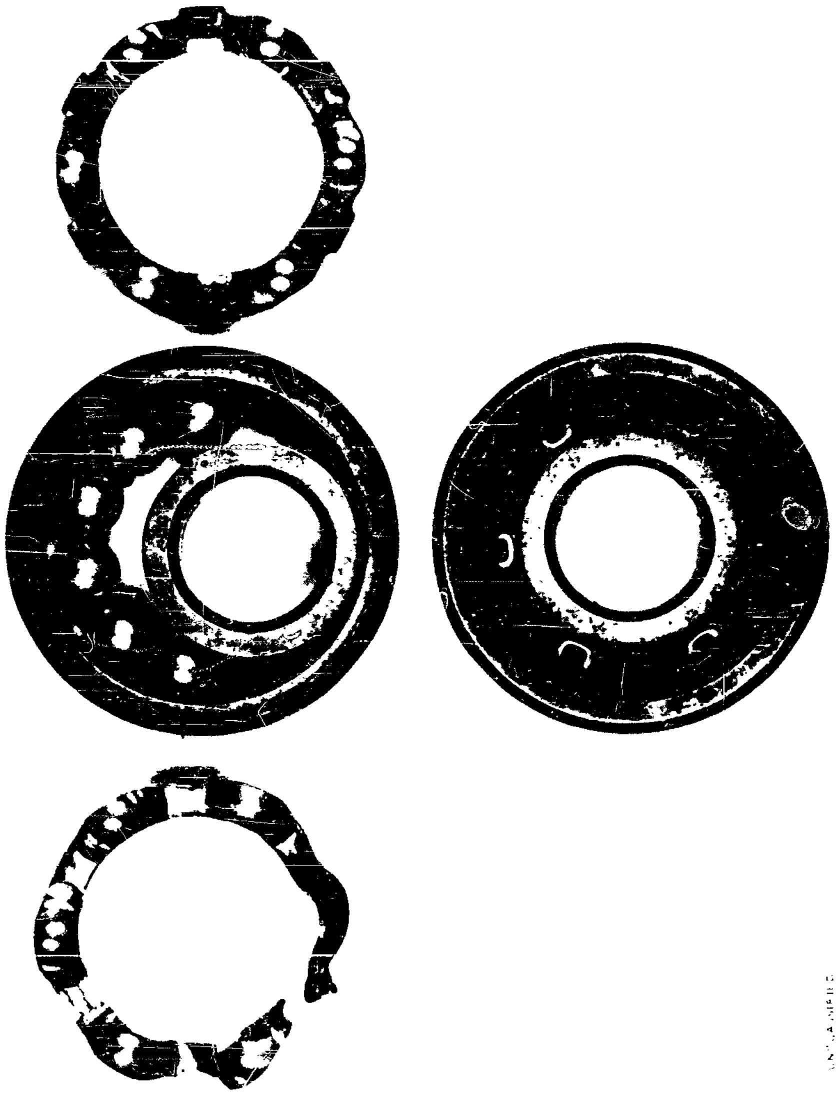

Figure A-7 Failed Molybdenum Disulfide Lubricated Bearings

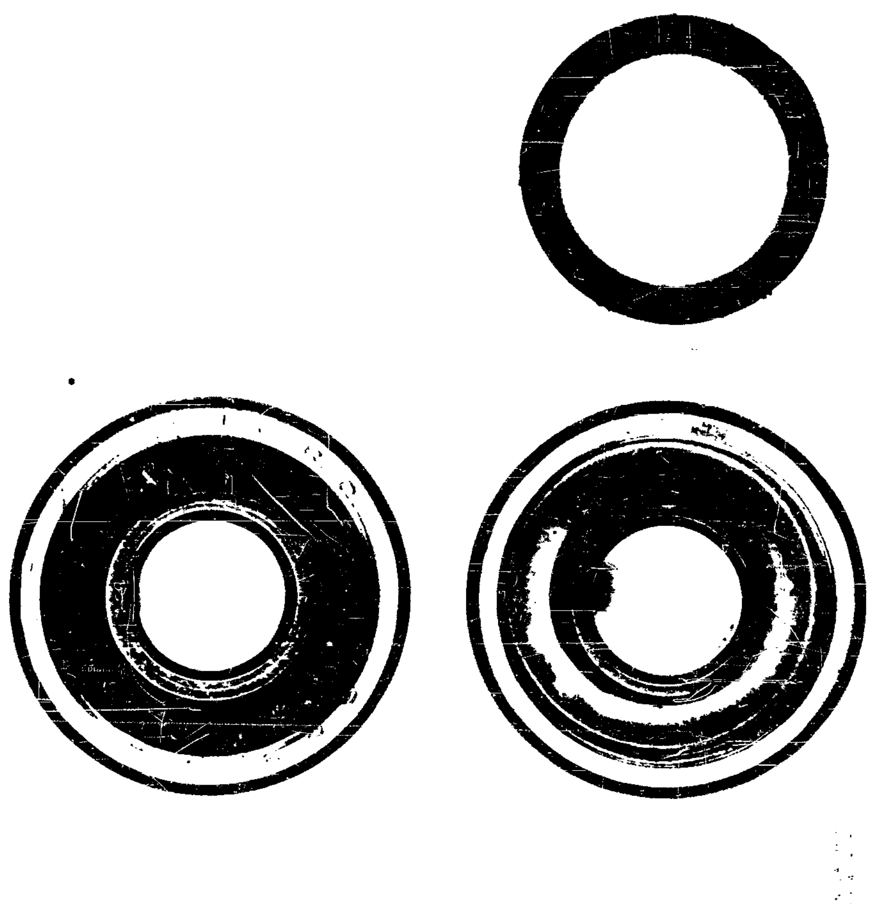

Figure A-8 Failed Bearings with Reinforced Polytetrafluoroethylene Retainers

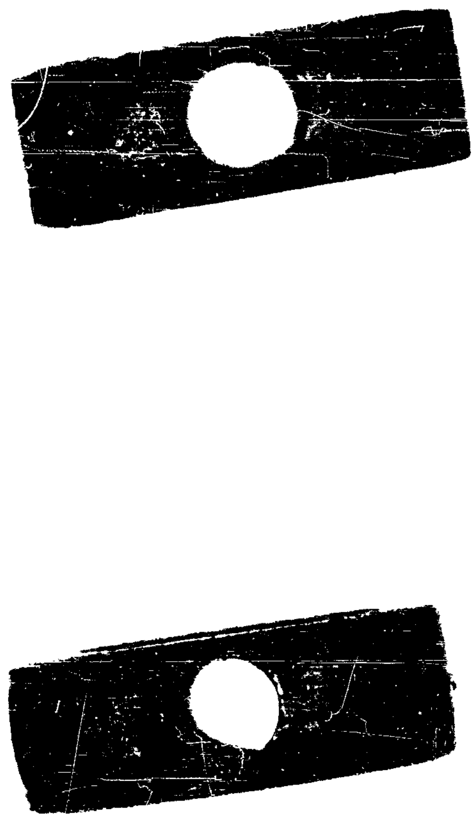

Figure A-9 Failed Bearings with Porous Nylon Retainers

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APPENDIX B

TABLES OF THE DATA OF TESTS WITH OILS, GREASES, DRY-FILM LUBRICANTS AND SPECIAL RETAINERS

Table B-1
TESTS WITH OIL LUBRICANTS

Test Number	Lubricant	Bearing Type(a)	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
1	Versilube F-50 chlorophenyl methyl polysiloxane, General Electric Co.	2	1 2	26.1 32.6	156	160 to 190	6×10^{-6} to 4×10^{-7}	–	–	Failed at 4,374 hr
2	Versilube F-50	4	1 2	28.3 20.6	162	150 to 185	2×10^{-7} to 9×10^{-9}	2:54 3:14 [illegible] 2:56 3:38 5:06 5:18 4:49 5:06 5:38 5:21	108 916 2,069 2,912 3,966 5,088 6,072 7,067 [illegible]162 [illegible]993 10,189	Failed at 13,652 hr
3	Versilube F-50 50% more volatile fraction removed by distillation	3	1 2	61.7 62.0	157	170 to 200	4×10^{-7} to $3 \times 10^{-[illegible]}$	1:56 1:06 9:14 9:19 9:17	759 1,342 1,577 2,256 3,150	Failed at 3,335 hr
4	Versilube F-50 50% more volatile fraction stripped	2	1 2 3	30 29 33	157	130 to 200	5×10^{-8} to 1×10^{-8}	–	–	Number 2 bearing failed at 1,856 hr and was replaced with Number 3 bearing which failed after 409 hr. Number 1 bearing still good after 2,265 hr.
5	Versilube F-50 50% more volatile fraction removed by distillation	3	1 2	54 53	159	102 to 140	760	0:49 1:12 2:27 3:49 3:57 4:14 4:00 4:18 4:00 3:35 4:25 3:18 3:07 3:03	1,565 2,383 3,051 3,843 4,997 5,986 7,038 7,978 8,916 10,116 11,063 12,068 12,655 13,748	Still running after 18,476 hr.
6	2/3 Versilube F-50 1/3 molybdenum disulfide powder	1	1 2	52 54	156	170 to 212	760 to 2×10^{-6}	0:50 0:40	47 98	Failed at 177 hr.
7	SF-96 dimethyl polysiloxane, General Electric Co.	4	1 2	32 38	159	170 to 175	2×10^{-7} to 9×10^{-8}	0:30 5:39	108 269	Failed at 347 hr.
8	SF-1017 methyl phenyl polysiloxane, 35% more volatile component stripped, General Electric Co.	2	1 2	42 30	158	151 to 181	3×10^{-6}	0:32 1:44 2:16	0 338 377	Failed at 458 hr. One bearing appeared satisfactory.
9	SF-1017 35% more volatile component stripped	4	1 2	35 41	157	143 to 170	5×10^{-7} to 2×10^{-6}	0:50 0:41 0:43 0:32 1:22 1:48	108 1,757 2,555 3,777 4,744 5,873	Failed at 6,066 hr. One bearing still satisfactory.

Table B-1 (Continued)

Test Number	Lubricant	Bearing Type[(a)]	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
10	DC 704 silicone vacuum pump oil, Dow Corning Corp	1	1 2	25 25	157	163 to 190	2×10^{-7} to 4×10^{-8}	10:05 4:18 9:02 7:37 7:55 5:00 4:02 3:35	107 268 461 1,248 2,070 2,237 2,382 2,[illegible]27	Failed at 2,603 hr.
11	QF-1-0026 fluorinated silicone oil, Dow Corning Corp.	3	1 2	15 25	273	16[illegible] to 190	2×10^{-8} to 8×10^{-10}	2:45 1:49 2:01 0:42	192 956 2,034 2,358	Failed at 2,474 hr
12	QF-6-7040 silicone oil	3	1 2	54 54	159	150 to 175	4×10^{-8} to 2×10^{-8}	0:25 7:43 5:23	151 463 1,139	Failed at 1,185 hr.
13	QF-1-0065 250 centistokes, fluorinated silicone oil, Dow Corning Corp.	3	1 2	51	157	150 to 190	5×10^{-8} to 2×10^{-8}	0:53 0:39 1:00 1:11 1:09	162 925 2,025 3,019 4,047	Still running after 9,874 hr
14	QF-1-0067 1000 centistokes, fluorinated silicone oil	3	1 2	85 85	157	140 to 200	$[illegible] \times 10^{-8}$ to $[illegible] \times 10^{-8}$	0:30 0:28 0:27 0:31 0:32	162 926 2,017 3,014 4,126	Still running after 9,998 hr.
15	Apiezon K petroleum base oil, AEI, Limited	3	1 2	50 56	159	165 to 200	5×10^{-6} to 9×10^{-9}	0:16 0:20 0:18 0:18 0:16 0:16 0:17 0:17 0:16 0:15 0:15 0:17 0:18	1,313 2,344 3,353 4,508 5,450 6,504 7,442 8,418 9,487 10,384 11,475 12,672 13,674	Still running after 18,297 hr.
16	Apiezon K	3	1 2	49 52	157	106 to 140	760	0:08 0:08 0:15 0:38 0:29 0:42 0:27 0:36 0:35 0:32 0:31 0:37 0:33 0:32 0:34	1,601 2,418 3,229 3,567 4,529 5,561 6,547 7,486 8,491 9,646 10,533 11,434 12,514 12,705 13,798	Still running after 18,511 hr.

Table B-1 (Continued)

Test Number	Lubricant	Bearing Type[a]	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
17	Apiezon K dissolved in 20% xylene	1	1 2	46 43	166	165 to 200	7×10^{-7} to 4×10^{-8}	0:43 0:43 0:40 0:29 0:28 0:39 1:04 1:10	47 869 2,079 3,207 4,096 5,001 5,142 6,051	Still running after 7,319 hr.
18	Apiezon J	3	1 2	41 40	–	170 to 200	5×10^{-8} to 7×10^{-10}	0:34 0:31 0:24 0:31 0:31 0:26	192 956 2,034 2,984 3,486 4,188	Still running after 7,093 hr.
19	Apiezon T	3	1 2	36 28	273	170 to 210	4×10^{-9} to 7×10^{-10}	5:53 0:49 1:24 1:31	193 359 527 690	Failed at 790 hr.
20	Apiezon C	3	1 2	46 43	274	135 to 200	4×10^{-9} to 1×10^{-9}	1:56 2:04 2:45 2:18	193 361 862 1,232	Failed at 1,713 hr.
21	Terresstic V-79, petroleum base oil, vacuum impregnated at 200 F, Humble Oil and Refining Co.	3	1 2	50 49	158	170 to 220	1×10^{-3} to 1×10^{-6}	–	–	Still running after 2,943 hr.
22	Diphenylbis - n dodecylsilane, Metals and Thermit Co.	3	1	31	157	166 to 1[illegible]	4×10^{-7} to 6×10^{-8}	2:10	885	Failed at 1,367 hr.
23	Diphenylbis-n-dodecylsilane	3	1 2	31 33	158	106 to 140	760	1:42 1:34 1:30 4:42 4:13 4:01 4:46 6:25 6:52 5:45 4:42 6:16 5:05	1,601 2,418 3,566 4,50[illegible] 5,540 6,526 7,464 8,469 9,624 10,511 11,577 12,661 13,737	Still running after 19,467 hr.
24	Oronite 8200 Hexa 2 ethyl butoxy disiloxane, Oronite Chemical	1	1 2	25 23	162	130 to 215	6×10^{-6} to 5×10^{-7}	2:27 3:04 6:45	3,235 3,883 4,052	Failed at 4,214 hr.
25	Oronite 8200	3	1 2	18 12	158	135 to 175	8×10^{-7} to 3×10^{-8}	2:24 6:34 10:26 12:39 2:53 3:06 4:01	19 212 1,323 2,209 3,412 4,534 5,172	Failed at 5,309 hr.

Table B-1 (Continued)

Test Number	Lubricant	Bearing Type(a)	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
26	Oronite 8515 85% Oronite 8200, 15% dioctyl sebacate	3	1 2	28 19	156	175 to 180	2×10^{-8} to 5×10^{-7}	0:58 1:01	131 298	Failed at 468 hr.
27	Oronite 8515	1	1 2	28 27	160	125 to 160	3×10^{-5} to 4×10^{-6}	–	–	Failed at 359 hr.
28	Cellulube 90 tri aryl phosphate, Celanese Corp.	2	1 2	13 29	162	184 to 190	8×10^{-6} to 2×10^{-6}	1:47	at start	Failed at 161 hr.
29	Cellulube 90	3	1 2	30 28	166	158 to 176	2×10^{-6} to 2×10^{-7}	0:55	167	Failed at 763 hr.
30	Cellulube 220	4	1 2	25 34	157	163 to 173	4×10^{-7} to 9×10^{-8}	3:43 1:55	108 267	Failed at 376 hr.
31	OS-124 isomeric five ring polyphenyl ether, Monsanto Chemical Co	3	1 2	72 69	162	151 to 170	4×10^{-6} to 6×10^{-8}	1:34 1:42 6:17 4:31 1:38	1,336 1,815 1,983 2,152 2,344	Failed at 2,176 hr.
32	OS-124	3	1 2	63 60	157	110 to 140	760	0:34 0:33 0:30 0:29 0:22 0:29 0:24 0:27 0:26 0:36 0:23 0:32 0:32	1,601 2,418 3,565 4,529 5,561 6,547 7,485 8,490 9,645 10,532 11,434 12,705 13,767	Still running at 18,440 hr.
33	Di-basic acid ester "A", Custom Lubricant Co.	3	1 2	38.7 49.8	275	159 to 170	2×10^{-7} to 4×10^{-8}	8:51 2:34 3:06	222 411 683	Failed at 801 hr.
34	above ester with molybdenum disulfide dispersion	4	1 2	35 45	275	140 to 160	3×10^{-7} to 8×10^{-8}	14:20 8:12 7:02	223 910 1,484	Failed at 1,736 hr.
35	Di-basic acid ester "C," Custom Lubricant Co.	3	1 2	51 43	275	150 to 190	3×10^{-7} to 6×10^{-8}	28:36 20:58 9:03	223 910 1,492	Still running after 2,717 hr.
36	Above ester with mobybcenum disulfide dispersion	4	1 2	52 33	270	160 to 180	3×10^{-7} to 6×10^{-8}	4:54 8:40 15:41	223 910 1,484	Failed at 2,766 hr.
37	Molykote M-55 colloidal dispersion of molybdenum disulfide in petroleum oil, Alpha Molykote Co.	2	1 2	35 35	162	140 to 160	8×10^{-7} to 2×10^{-7}	1:47 2:32 2:52 1:35 2:02	19 362 1,036 1,514 2,815	Failed at 2,908 hr.

(a) Bearing Types: 1 - 440C stainless steel, ribbon retainer, double shielded.
2 - 52100 chrome steel, ribbon retainers, double shielded.
3 - 440C stainless steel, Synthane retainers, double shielded.
4 - 52100 chrome steel, Synthane retainers, double shielded.

Table B-2

TESTS WITH GREASE LUBRICANTS

Test Number	Lubricant	Bearing Type[a]	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Const Time (min:sec)	Elapsed Test Time (hr)	Results
1	Versilube C-300 Versilube F-50 with lithium soap thickener, General Electric Co.		1 2	91 101	160 and 158	132 to 220	2×10^{-6} to 2×10^{-8}	1:53 2:05 2:15 2:16 3:17 2:35 2:10 1:02 1:47	2,233 3,050 4,052 5,013 6,046 6,983 8,099 9,060 9,587	Failed at 9,612.5 hr.
2	Versilube G-300		1 2	55 65	276	145 to 175	5×10^{-5} to 4×10^{-7}	3:31 2:42 0:49 4:22	153 1,053 1,984 3,004	Still running after 8,255 hr.
3	Versilube G-300		1 2	[illegible] 56	273	221 to 230	5×10^{-5} to 4×10^{-7}	2:44 4:13 6:14 5:19	153 1,045 1,975 2,995	Still running after 8,244 hr.
4	Versilube G-300		1 2	54 56	277	290 to 300 (except 145 to 160 for 600 hr)	5×10^{-5} to 4×10^{-7}	3:02 3:07 3:59 1:40	153 1,053 1,985 3,004	Failed at 4,359 hr.
5	Aeroshell No. 15 Extreme Temperature Range Grease – methyl phenyl silicone oil with dye thickner, Shell Oil Co.		1 2	96	157	160 to 225	3×10^{-8} to 9×10^{-9}	0:34 2:20 2:36 1:55 3:33 5:10 4:49 3:58 4:20 4:43 3:43	2 163 953 2,013 2,912 4,063 5,071 6,064 6,902 7,200 8,261	Still running after 13,364 hr.
6	QG-5-0010 fluorosilicone oil with soap thickner, Dow Corning Corp.		1 2	93 93	–	160 to 190	1×10^{-9} to 8×10^{-10}	0:30 1:02 0:55 0:46 0:36	240 789 2,034 3,007 3,508	Failed at 3,797 hr.
7	QC-2-0026 fluorosilicone grease, Dow Corning Corp.		1 2	97 104	274	184 to 212	4×10^{-7} to 4×10^{-8}	0:53	192	Failed at 340 hr.
8	High vacuum silicone grease, Dow Corning Corp.		1 2	89 62	139	163 to 172	1×10^{-7} to 8×10^{-8}	0:21 5:56 2:42	2 165 309	Failed at 485 hr.
9	EG 429 silicone oil based grease, Marlin-Rockwell Corp.		1	51	158	160 to 200	5×10^{-8} to 1×10^{-8}	3:34 3:00 2:46 4:09 3:22	162 1,184 1,999 3,004 4,110	Still running after 9,691 hr.

Table B-2 (Continued)

Test Number	Lubricant	Bearing Type[(a)]	Bearing Number	Initial Weight Of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
10	EG 309 silicone oil based grease		1	49.0 60	158	165 to 200	5×10^{-8} to 1×10^{-8}	2:32 4:03 5:53 6:35 7:43	162 719 1,130 1,970 2,954	Still running after 9,421 hr.
11	MLG-61-92 high temperature grease, Aeronautical Systems Division, USAF		1 2	61 67	273	160 to 175	2×10^{-6} to 2×10^{-7}	–	–	Still running after 2,755 hr.
12	MLG-62-142 silicone oil base grease, ASD, USAF		1 2	69 79	274	155 to 160	2×10^{-6} to 2×10^{-7}	–	–	Still running after 2,752 hr.
13	RPM No 5 grease meeting MIL-G-3278, Standard Oil of Calif.		1 2	97 111	159	145 to 215	2×10^{-7} to 4×10^{-8}	0:49 0:36 1:10 2:10 3:42 4:28 7:00 8:14 5:46 5:24	2 670 863 1,030 1,364 1,580 1,869 2,061 2,986 3,517	Failed at 3,820 hr.
14	Chevron OHT Grease petroleum oil thickened with sodium stearate, Standard Oil of Calif.		1 2	47 48	162	151 to 155	8×10^{-7} to 3×10^{-7}	3:11 10:32	139 882	Failed at 969 hr.
15	Chevron Duraplex EP Heavy Grease petroleum oil thickened with complex calcium soaps		1 2	49 45.0	159	155 to 175	4×10^{-8} to 2×10^{-8}	6:21 1:30 0:51 4:51	110 725 1,085 1,775	Failed at 1,866 hr.
16	Chevron Industrial Grease, Heavy petroleum oil thickened with sodium soap		1	84	157	143 to 165	9×10^{-8} to 2×10^{-8}	0:34 0:58 1:41 1:13 1:51	2 600 959 2,018 2,344	Failed at 3,160 hr. Both bearings filled with decomposed grease.

(a) All bearings were 440C stainless steel with ribbon retainers and double shielding.

Table B-3

TESTS WITH MoS_2-BASED LUBRICANTS

Test Number	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
1	Everlube 811 sodium silicate bonded MoS_2 applied to races and retainers only, after grit blasting; Everlube Co.	159	160 to 180	8×10^{-6} to 9×10^{-8}	1:7 6:17 4.49 5:56 4:31	5.6 771 1,419 2,021 2,181	Failed at 2213 hr.
2	Same as above	162	100 to 180	6×10^{-6} to 1×10^{-7}	–	–	Test stopped at 876 hr. One original bearing still good, the other failed at 238 hr.; replacement failed after 174 hr.
3	Same as above	275	170 to 200	8×10^{-7} to 2×10^{-7}	11:37	167	Test stopped a. 245 hr. One bearing failed, the other was satisfactory. Reversal test with 244 reversals.
4	Same as above	159	140 to 185	2×10^{-6} to 2×10^{-7}	6.53 5:18 2:41 3:0	82 223 391 726	Failed at 772 hr. Start-stop-reverse test with 771 reversals.
5	Same as above	275	RT to 172	5×10^{-6} to 9×10^{-8}	7:43 6:43	61 2.31	Failed at 342 hr. One bearing had broken retainer; second was satisfactory.
6	Same as above	274	RT to 122	760	–	–	One bearing failed at 132 hr., its replacement failed after 114 hr. Other bearing failed at 246 hr.
7	Everlube 811 Sodium silicate bonded MoS_2 applied to races and retainers after special pretreatment	157	160 to 170	8×10^{-6} to 8×10^{-7}	5:14 3:39 4:21 3:56	5.6 753 1,232 1,761	One bearing failed at 1862 hr.; the other still satisfactory.
8	Same as above	158	RT to 140	760 to 2×10^{-7}	–	–	One bearing failed at 28 hr., the other still in good condition.
9	Same as above	157	150 to 158	8×10^{-6} to 8×10^{-7}	4:14 6:50 4:30	5.6 656 1,664	Failed at 1,796 hr.

Table B-3 (Continued)

Test Number	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
10	Everlube 811 applied to the races, retainers and balls after special pretreatment	275	180 to 190	3×10^{-3} to 2×10^{-7}	9:41	226	One bearing failed at 483 hr., second bearing satisfactory.
11	Same as above	269	180 to 200	3×10^{-3} to 4×10^{-7}	21:29	225	Failed at 296 hr.
12	Polychem Epoxy bonded MoS_2 applied to races and retainers. Poly Chem Company	162	90 to 160	5×10^{-6} to 1×10^{-7}	–	–	Stopped at 467 hr. One bearing failed at 308 hr., second failed at 467 hr.
13	Same as above	160	140 to 170	5×10^{-6} to 2×10^{-7}	7:24 5:56	82 725	Failed at 771 hr. Stop-start-reverse test with 771 reversals.
14	Same as above	275	RT to 140	760 to 2×10^{-6}	1:1	66	Failed at 88 hr.
15	MoS_2 film applied with epoxy binder, after special surface treatment. Poly Chem Company	157	159 to 173	2×10^{-6} to 3×10^{-7}	1:3 0:56 0:14	57 181 305	Failed at 305 hr. One bearing frozen, other in fair condition. Start-stop-reverse with 305 reversals.
16	MoS_2 film bonded to races and retainers with colloidal quartz after special pretreatment, Microseal Products, Inc.	162 and 160	160 to 180	7×10^{-6} to 1×10^{-7}	–	–	Test stopped at 670 hr. One bearing failed at 7.6 hr due to ball coming out of retainer. Other bearing failed at 670 hr.
17	Same as above	158	RT to 100	760 to 2×10^{-6}	–	–	Failed at 10.5 hr. Reversal test with 10 reversals.
18	Same as above	275	RT to 150	760 to 2×10^{-6}	0:56	66.5	Failed at 87.5 hr.

Table B-3 (Continued)

Test Number	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
19	Teleflex S.W. 16 MoS_2 bonded to races and retainers with low-temperature ceramic, Teleflex, Inc.	158	RT to 180	1×10^{-6} to 4×10^{-7}	4:8	17.5	Failed at 135 hr.
20	Teleflex S.W. 16 bonded to races, retainers and balls, Teleflex, Inc.	158	RT to 190	760 to 7×10^{-6}	0:14	27	Failed at 28.9 hr. One bearing still appeared satisfactory.
21	Teleflex S.W. 25 MoS_2 bonded to races and retainers with low-temperature ceramic, Teleflex, Inc.	160	RT to 187	760 to 4×10^{-7}	4:12	17.5	Failed at 157 hr.
22	Teleflex S.W. 25 bonded to races, retainers and balls, Teleflex, Inc.	157	RT to 143	760 to 2×10^{-6}	2:26	18.7	Failed at 26.5 hr.
23	Microsize MoS_2 applied by dusting and burnishing to dry bearing	160	RT to 141	760 to 2×10^{-6}	6:27	18.7	Failed at 30.8 hr.
24	Hi-T-Lube MoS_2 bonded to races and retainers, General Magna-Plate	275	150 to 170	6×10^{-7} to 2×10^{-7}	15:50	144	Failed at 457 hr.
25	Hi-T-Lube bonded to races, retainers and balls	275	160 to 184	6×10^{-7} to 4×10^{-8}	30:27 7:42 8:20 2:50	144 693 1,366 1,533	Failed at 1,533 hr.
26	Hi-T-Lube bonded to the races, retainers and balls	273	160 to 170	8×10^{-7} to 2×10^{-8}	15:11 5:54 3:6	214 379 1,054	Start-stop-reverse test. One bearing failed with broken retainer at 1080 hr. (1080 reversals). Bearing replaced and test continuing after 1173 hr. (1173 reversals).

Table B-3 (Continued)

Test Number	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
27	Hi-T-Lube bonded to the races, retainers and balls	273	95 to 120	760	9:19 9:2 8:4 9:0	213 1,043 1,998 2,584	Failed at 4261 hr.
28	Proprietary coating bonded to races and retainers, Reher-Simmons, Inc.	275	180 to 190	1×10^{-3} to 3×10^{-7}	7:05	70	Failed at 106 hr, one bearing still satisfactory.
29	Proprietary coating applied to the races, retainers and balls, Reher-Simmons, Inc.	270	195 to 215	1×10^{-3} to 1×10^{-7}			Failed at 209 hr.

NOTE: All bearings were 440C stainless steel with ribbon retainers and unshielded.